ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
ISSN: 1584 - 2665

STRENGTHENING OF REINFORCED CONCRETE RECTANGULAR COLUMNS WITH GLASS FIBRE REINFORCED POLYMERS

Salahaldein ALSADEY[1], Abdelnaser OMRAN[1] , JAYAPRAKASH [2]

[1]School of Housing, Building and Planning, Universiti Sains Malaysia, Minden, Pulau Pinang, MALAYSIA
[2]School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal, Penang, MALAYSIA

Abstract
This study exemplifies the results of comprehensive experimental investigation on the behaviour of axially loaded Reinforced Concrete (RC) rectangular columns repaired with Glass fibre Reinforced Polymer (GFRP) Fabrics. Totally ten RC rectangular specimens were fabricated and tested under axial compression load. Two specimens were retained as control specimen and the remaining eight specimens were partially pre-cracked to 60% of the ultimate failure load of the control specimen and repaired using GFRP fabrics strips. This study investigated three variables included slenderness ratio, spacing amount and orientation, and number of plies of GFRP strips. The result of this investigation indicates that the gain in compressive strength varied between 31.58 % and 50 %. It was also found that the above mentioned parameters affect the ultimate compressive load capacity and modes of failures of the repaired rectangular columns. Furthermore, the experimental result shows better agreement with existing theoretical model.
Keywords: Glass Fibre Reinforced Polymer, Ultimate load, Confined, Strengthening.

1. INTRODUCTION

Several traditional techniques have been used for repairing reinforced concrete columns such as concrete jackets and steel plates. The main purpose of confinement is to increase the load carrying capacity and ductility of the reinforced concrete columns. It has some disadvantages such as increase of dead load; increase of owns section of column which leads to increase its flexural stiffness. This steel plate jacketing system is not a feasible technique to use in aggressive environments. Engineers have used traditional materials such as wood, steel, and concrete to confine and improve the structural behaviour of concrete members. Since 1980, there has been a worldwide increase in the use of composite materials for the rehabilitation of deficient RC structures. One important application of this composite retrofitting technology is; the use of Fibre Reinforced Polymer (FRP) jackets to provide external confinement to RC columns when the existing internal transverse reinforcement is inadequate (Yousef, 2006). Fibre Reinforced Polymer (FRP) is a composite material comprises fibre in a polymer matrix. The FRP is typically applied with an epoxy resin. The epoxy resin is used to align the fibres in proper direction and bond the wrap with the structural member. The advantages of the FRP include high strength to weight ratio, high stiffness, corrosion resistance, high specific strength, and durability (Raghu et al., 2001). While FRP can be used to strengthen many different structural members such as beams, columns, slabs and chimneys. A structure probably needs upgrading due to the increased loading and/or reduction in the load carrying capacity, corrosion of steel reinforcement, chemical attacks, aggressive environments, construction errors, and old design codes. For example, bridges are sometimes designed according to standard specifications however, due to increased traffic volume; they probably need to improve the load carrying capacity and structural performance of the structures. Recently, Fibre Reinforced Polymers (FRP) has been used to repair and rehabilitate concrete columns, beams and slabs. This FRP composite has many potential characteristics as compared to the use of traditional techniques. FRP sheets have a high strength to weight ratio, very high resistance to corrosion and chemical attacks which makes them, unlike steel plates and concrete jackets, suitable for structures subjected to aggressive environment. In addition, FRP sheets are easy to handle in site and do not add to the dead load of the structure. The ACI report (1996), reported that FRP products were first used to reinforce concrete structures in the mid 1950s however, in spite of the earlier research on the use of FRP reinforcement in concrete, commercial application of the FRP in concrete was not recognized until the late 1970s.

2. THEORETICAL MODELS

2.1 International Conference of Building Officials (ICBO)-1997

For rectangular sections with an aspect ratio (h/b) less than 1.5, the enhanced compressive strength can be calculated with the following equation:

$$f'_{cc} = f'_c(1+5\,\rho_f \cos^2\theta) \quad (1)$$

where, $\rho_f = 2t_f \frac{(b+h)}{bh}$, $\theta \leq 45°$

The axial load capacity enhancement due to the longitudinal fibres is

$$\Delta P = A_f \cos^2\theta\, f_f \quad (2)$$

where, A_f = cross-sectional area of the fibre sheets, $f_f = 0.002E_f \cos^2\theta < 0.75 f_{fu}$

A higher fibre strain may be used if the section is effectively confined.

2.2. Mander *et al.*, (1988) Model

Mander et al. (1988) proposed a model to calculate the increase in concrete compressive strength due to confining pressure provided by transverse reinforcement in reinforced concrete columns. The model has been extended to the case of FRP-confined circular and square reinforced concrete by sections several researchers (Wang and Restrepo 2001). For rectangular sections in which the confining pressures in two orthogonal directions:

$$f'_{cc} = \alpha_1 \alpha_2 f'_c \quad (3)$$

where

$$\alpha_1 = 1.25[1.8\sqrt{(1+7.84\, f_{lx}/f'_c)} - 1.6\, f_{lx}/f'_c - 1] \quad (3.1a)$$

$$\alpha_2 = [1.4\, f_{ly}/f_{lx} - 0.6(f_{ly}/f_{lx})^2 - 0.8\sqrt{f_{lx}/f'_c} + 1] \quad (3.2\ b)$$

$$f_{lx} = f_{ly}.$$

$$f_{lx} = \rho_{jx}\,(0.005\, E_p) \quad (3.4a)$$

$$f_{ly}. = \rho_{jy}\,(0.005\, E_p) \quad (3.5b)$$

where, Ep is the elastic modulus of the FRP jacket, 0.005 represents the transverse strain in the FRP jacket is provided in the determination of lateral confining stresses when the nominal compressive strength of the concrete at ultimate state is evaluated.

The reinforcement ratio ρ_{jx} and ρ_{jy} are defined as follows:

$$\rho_{jx} = 2\,(t_j / t_y) \quad (3.6a)$$

$$\rho_{jy} = 2\,(t_j / t_x) \quad (3.7b)$$

where, t_j is the nominal jacket thickness, t_x and t_y are the overall column cross-section dimensions.

2.3. BS 8110 (1997)

A rigorous approach would entail the consideration of the confinement effect of transverse steel links; however, this is implicitly accounted for in the following formula for the axial load capacity of the reinforced concrete column with nominal transverse links:

$$N = 0.67 f_{cu} Ac + A_s f_y \quad (3.8)$$

(without safety of factor: 1.5 for concrete, 1.05 for steel)

where, A_s = total area of longitudinal reinforcement, A_c = net area of the concrete

3. RESULTS AND DISCUSSION

This part discusses the experimental investigation of reinforced concrete rectangular columns bonded externally with Glass Fibre Reinforced Polymer (CFRP) fabrics. However, it presents the results of series CL (size: 100mm x 150mm x 900mm) and series CS (size: 100mm x 150mm x 500mm). Ten rectangular columns were tested with variables included spacing of GFRP strips (60mm, 100mm, and 140mm), orientation (0° and ±45°), layers of GFRP (1 and 2 layers or plies), and slenderness ratio (6.0 and 3.33). It also attempts to discuss the comparison of experimental results with existing theoretical models.

Table 1: Result of average compressive strength of cube

Periods	Compressive Strength (MPa)			Average
	Cube 1	Cube 2	Cube 3	
7	23.30	22.50	23.50	23.10
14	28.25	26.75	26.99	27.40
28	29.99	31.00	29.01	30.00

3.1. Strength of Concrete

The test results of concrete strength cubes at the age of 7, 14 and 28 days are shown in Table 1. Figure 1 shows the average compressive strength of concrete cube at various ages.

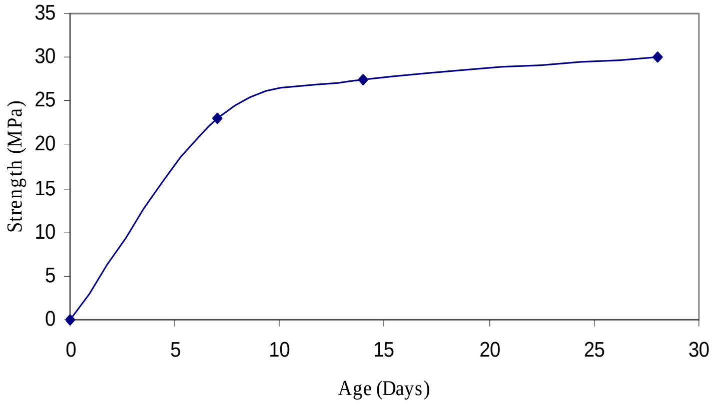

Figure 1. Concrete strength versus time

3.2. Ultimate Failure Load and Mode of Failure

Series CL: In control specimen CL1, first crack in the specimen observed at a compressive load of 260 kN. As applied load increased, cracks were developed in the vertical direction at the top of the column. At last, the top end of the specimen failed in compression at a load approximately of 380 kN. In the precraking phase of the specimens CL2, and CL4, the observed cracking patterns of precracked specimens were similar to the control specimen, whereas there was no crack observed in columns CL3 and CL5. After repairing, these specimens CL2, CL3, CL4 and CL5, were failed at a failure load approximately of 560 kN, 540 kN, 500 kN, and 560 kN respectively. In the GFRP strengthened columns, the failure was associated with concrete crushing with sudden rupture of GFP strips at the top or bottom ends of columns. When the confinement of GFRP discrete strip fails, the concrete core was unable to withstand the load, which corresponds to a stress significantly over compressive strength of concrete. The rupture of the confinement thus triggers a sudden failure mechanism. Popping noises were observed at various stages of loading which was probably due to the micro cracking of the fibre strips. Besides, failure of GFRP strips was observed at or near the corner of the specimens due to the stress concentrations. The maximum gain achieved in specimens CL2, CL3, CL4, and CL5 with respect to control specimen were approximately of 48%, 42%, 32%, and 48% respectively. It can be seen that the confinement of reinforced rectangular columns with GFRP strip increases the compressive strength of the column.

Figure 2(a): Crushing of concrete for control specimen CL1

When compared with the control specimens. Figures 2 (a) and 4(a) show the failure patterns for control and precracked-repaired specimens in series CL. Table 2 shows the summary of experimental results for control and repaired specimens in series CL.

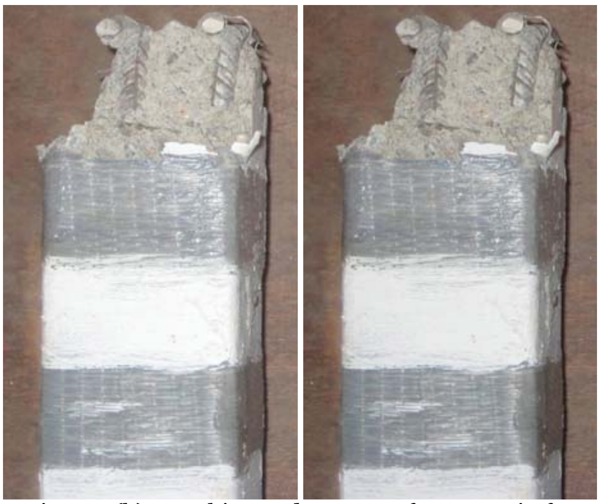

Figure 2(b): Crushing and rupture of GFRP strip for repaired specimen CL2

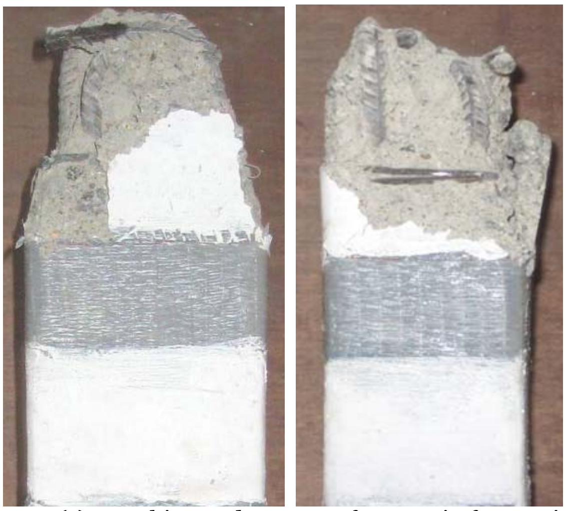

Figure 2(c): Crushing and rupture of FRP strip for repaired specimen CL3

Figure 2(d): Crushing and rupture of FRP strip for repaired specimen CL4

Figure 2(e): Compression failure for repaired specimen CL5

Series CS: Similarly, the control specimen CS1 in series 2 failed in compression at a failure load of 360 kN. The behaviour of the precracked specimen was similar to the control specimen. The repaired specimen CS2 failed in GFRP rupture with compression failure at top end of the column at a failure load of 540 kN. However, the specimen CS3, and CS4 attained a failure of crushing of concrete and rupture of GFRP wrap at an ultimate compressive load of 500 kN and 480 kN respectively. The specimen CS5 failed in cracking in the unstrengthened portion of concrete is near the bottom of the column. The obtained gain in percentage of enhancement of compressive load of the repaired rectangular columns CS2, CS3, CS4, and CS5 with slenderness ratio 3.33 was 50%, 39%, 34%, and 45% greater over the control specimen.

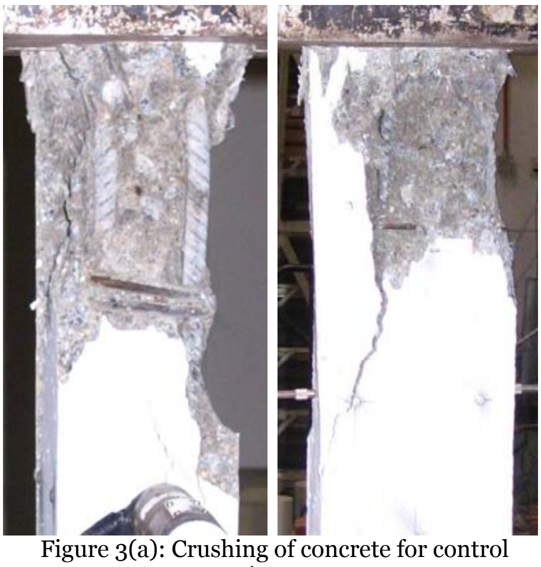

Figure 3(a): Crushing of concrete for control specimen CS1

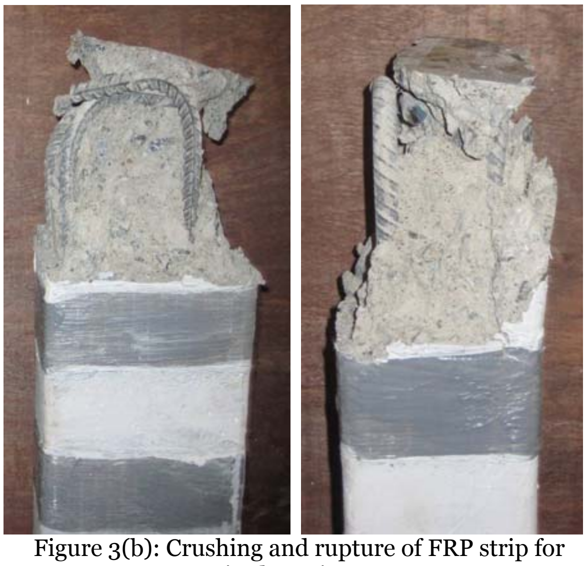

Figure 3(b): Crushing and rupture of FRP strip for repaired specimen CS2

Figure 3(c): Crushing and rupture of FRP strip for repaired specimen CS3

Figure 3(e): Crushing and rupture of FRP strip for repaired specimen CS5

Table 1 shows the external strengthening GFRP patterns and test results of the control and precracked-repaired specimens. Table 2 shows the summary of experimental results for control and repaired specimens in series CS. Figures 3 and 4(b) depicts the failure patterns of the control and precracked-repaired specimens in series CS

Key Observation:

Results shows that the percentage gain in compressive load of the repaired specimens was ranging from 32 % to 50 % greater over the control specimens.

Figure 3(d): Crushing and rupture of FRP strip for repaired specimen CS4

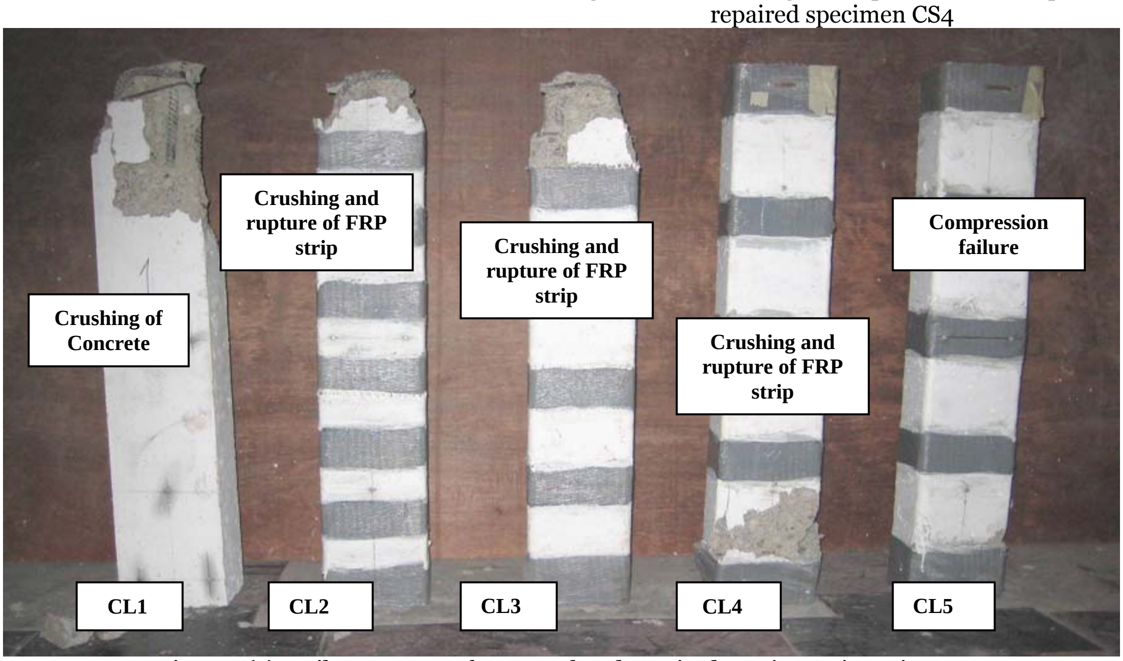

Figure 4(a): Failure patterns for control and repaired specimens in series CL

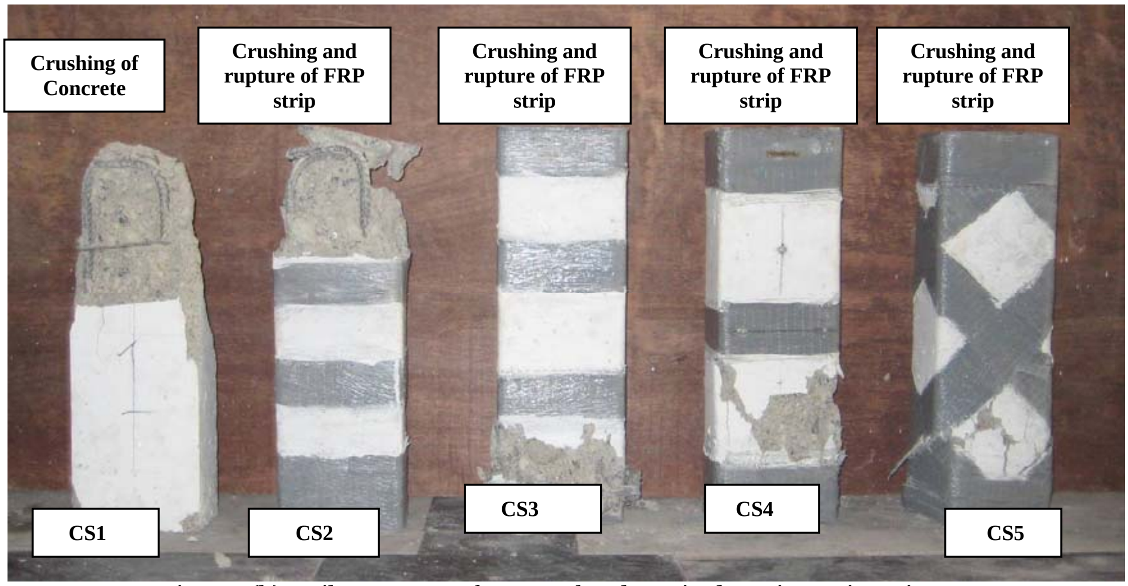

Figure 4(b): Failure patterns for control and repaired specimens in series CS

Table 2: Summary of experimental results for control and repaired specimens in series CL and CS

Specimen Designation		Spacing/No of Plies/ Oreintation of GFRP strips	Max. Displacement* (mm)	Axial Stress (N/mm²)	Failure Load (kN)	Increment (%)
CL	CL1 (C)	--	3.86	25.33	380	--
	CL2 (P-R)	60mm / 1No./ 0°	3.36	37.33	560	47.37
	CL3 (P-R)	100mm / 1 No./ 0°	6.76	36.00	540	42.12
	CL4 (P-R)	140mm / 1 No./ 0°	7.92	33.33	500	31.58
	CL5 (P-R)	140mm / 2 No./ 0°	6.56	37.33	560	47.37
CS	CS1 (C)	--	3.95	24.00	360	--
	CS2 (P-R)	60mm / 1No./ 0°	5.05	36.00	540	50.00
	CS3 (P-R)	100mm / 1 No./ 0°	5.02	33.33	500	38.89
	CS4 (P-R)	140mm / 1 No./ 0°	4.47	32.00	480	33.33
	CS5 (P-R)	140mm / 1 No./ 45°	5.60	34.67	520	44.44

* Measured Maximum Displacement before failure load

3.3 Stress-Strain Profile

Figures 5 and 6 portray the axial stress versus axial strain for control and precracked-repaired specimens in series CL and CS representing a slenderness ratio of 6 and 3.33 respectively. In Series CL, the axial strain curves for specimens CL2 and CL3 repaired with GFRP strips spaced at 60 mm 100 mm were stiffer than specimens CL4 and CL5 with strips spacing of 140 mm.

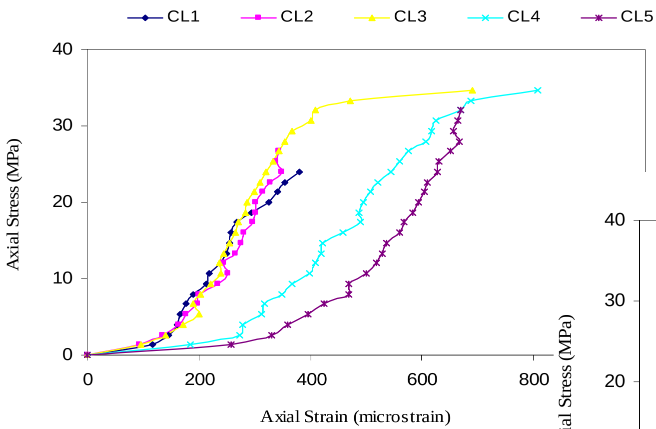

Figure 5: Axial stress-strain curves for control and repaired specimens in series CL

Whereas, in series CS, the repaired columns shows similar trend in axial strain curves probably due to the effect of lower value of slenderness ratio (i.e. 3.33). It can be seen from Figure 5, increasing the spacing between the GFRP strips decreases

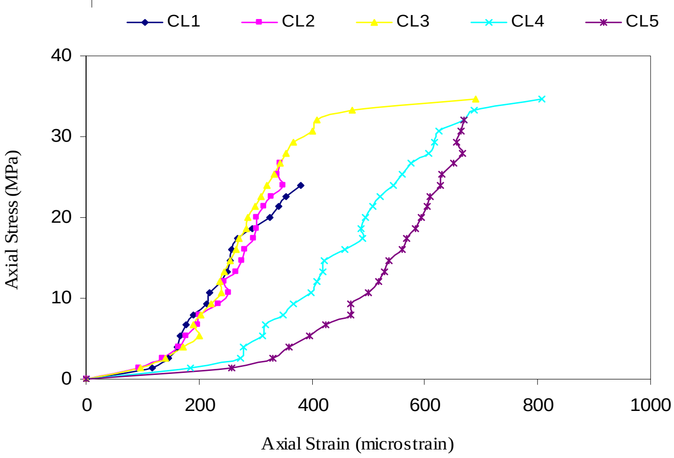

Figure 6: Axial stress-strain curves for control and repaired specimens in series CS

the stiffness of the axial strain curve. The figures also show that the repaired columns attained higher axial strain value than the control specimen for the same load at failure.

Fibre strain Response*:* Figure 7 indicates the axial load versus GFRP fibre strain for repaired rectangular columns. One strain gauge used in each repaired specimen. The fibre strain was measured by placing strain gauge in the fibre direction of the strip at the top of the specimen. It shows that the fibres strain values of the repaired columns were very minimal up to the load approximately of 20MPa, however, strain values increased at higher rate probably due to the formation of crack. The measured maximum strain value of fibre was 0.008, which is less than nominal strain value of 0.02.

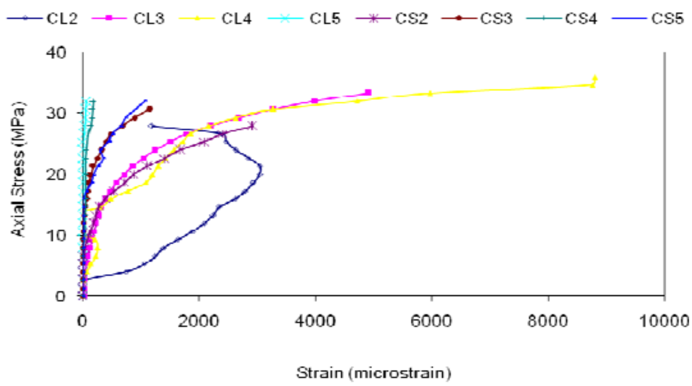

Figure 7: Axial load versus strain in fibres for repaired specimens

3.4. Test Parameters

This investigation studied three different variables; namely spacing, orientation, layer of GFRP strips and slenderness ratio. The purpose was not only to determine the ultimate load carrying capacity but also to identify the most suitable wrapping pattern of the repaired rectangular columns.

3.4.1. Effects of Spacing of GFRP strips

Figures 8 and 9 illustrate the comparison of compressive load for repaired specimens with different spacing of GFRP strip in series CL and CS respectively. From Figure 8, it can see that the specimen CL2 repaired with spacing of 60 mm attained an enhancement of 12 % greater than specimen CL4 with strips spaced at 140 mm. Similarly specimen CL3 spaced at 100mm gained 8% greater than the specimen CL4. Similarly the specimens CS2 (spacing = 60 mm) and CS3 (spacing = 100 mm) attained 12.5% and 8 % greater than the specimen CS4 with strips spaced at 140 mm.

Key Observation:

It was found that the increasing the spacing of strips decreases the ultimate compressive load of the repaired specimens.

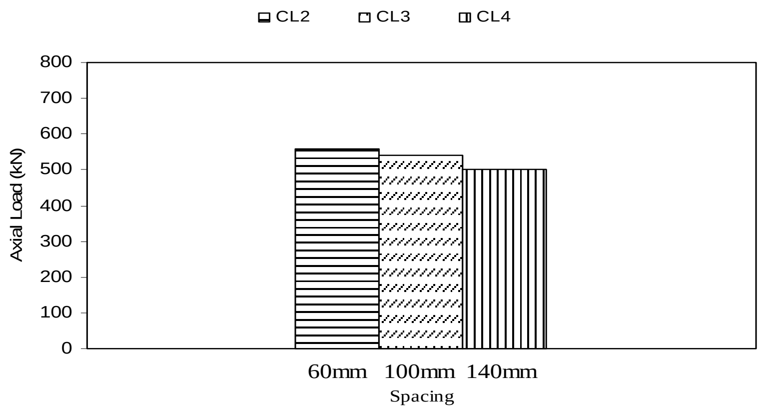

Figure 8: Comparison of compressive load with different spacing (60mm 100mm, and 140mm) of GFRP strips for repaired specimens in series CL

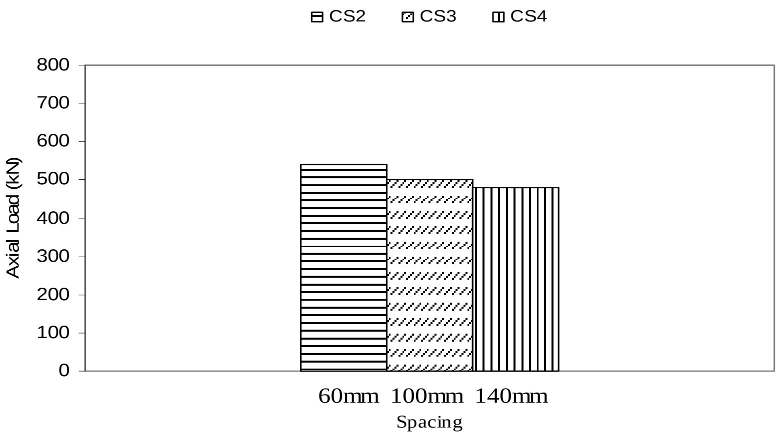

Figure 9: Comparison of compressive load with different spacing (60mm 100mm, and 140mm) of GFRP strips for repaired specimens in series CS

3.4.2. Effect of Layers of GFRP Strips

Figure 10 shows the results of a comprehensive experimental investigation on the behaviour of axially loaded rectangular columns strengthened with different GFRP discrete strips. From the result, specimen CL5 with two plies attained an enhancement of 12% greater than the specimen CL4 with single ply. It was found that, the confinement of columns with GFRP wrap increased with the increase number of layers of GFRP discrete strips. This behaviour is similar to the Kumutha *et al.,* (2005) but they studied with continuous wrapping system but not in the form of discrete strips.

Key Observation:
It indicates that higher percentage of compressive load could be achieved by increasing the number of layers in the form of discrete GFRP strips.

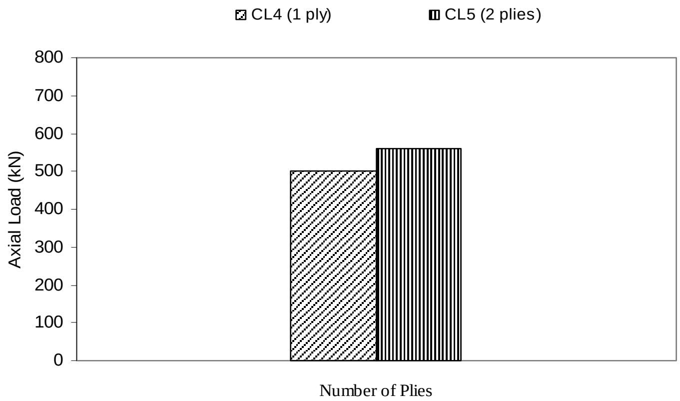

Figure 10: Comparison of compressive load with different number of layers (1 and 2 plies) of GFRP strips

3.4.3. Effect of orientation of GFRP strips

Figure 11 shows the comparison of ultimate compressive load for repaired specimen with 0° and ±45° orientations. Specimen CS5 repaired with ±45° strips orientation attained a gain in compressive load of approximately 7.69% greater than the specimen CS4 orientated with 0° strips. This confirms that the specimen strengthened with two directions (i.e. ±45° orientation) had better and significant effect on the strength and stiffness behaviour of rectangular columns, however, the result of Li *et al.*, (2003) does not show any significant effect with change in orientation because they wrapped the specimens in one direction with a orientation of 45° only.

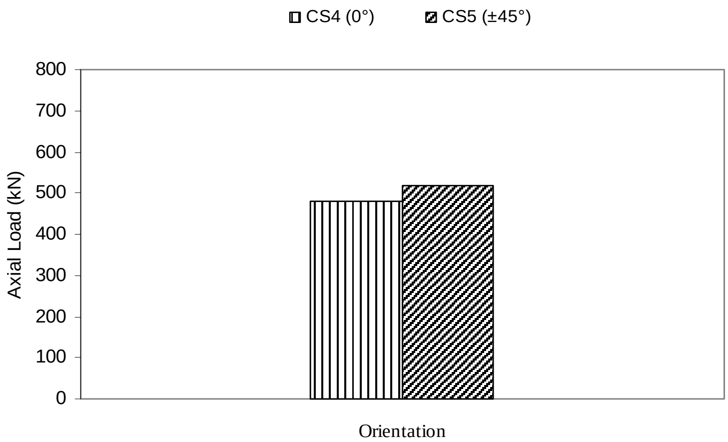

Figure 11: Comparison of compressive load with different fibre orientations (0° and ±45°)

Key Observation:
Results shows that specimens with ± 45° orientation attained better enhancement than with 0° orientation. It was also found that the orientation of ±45° shows significant result because the fibre strips were orientated in two directions.

3.4.4 Effect of Slenderness Ratio

Figure 12 shows the effect of slenderness ratio of specimens from series CL and series CS with slenderness ratio of 6 and 3.33, respectively. The strengthened specimens CS4 and CS2 in series CS with the slenderness ratio of 3.33 attained an enhancement approximately of 50% and 34% greater than the specimens in series CL with slenderness ratio of 6.

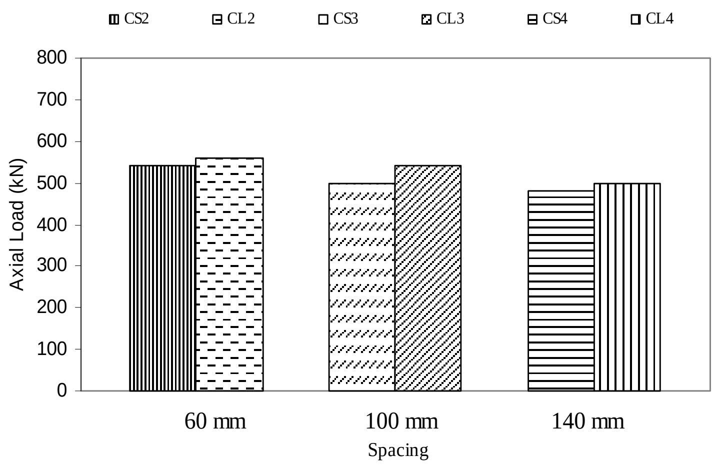

Figure 12: Comparison of compressive load with different slenderness ratio (6.0 and 3.33) for series CL and CS

Key Observation:
Results confirm that the column with slenderness ratio of 3.33 contributed a maximum enhancement of 50% greater than column with slenderness ratio of 6.0.

3.5 Theoretical Investigation

The design guidelines recommendations for columns strengthened with externally bonded FRP are generally based on a confinement model, which is, based on experimental tests with carry some limitations. Some of the proposed equations and guidelines are developed from the results of fully confined specimens. This research intend to such theoretical models for columns strengthened with discrete strips. The test results obtained from experimental work were compared with existing ICBO (1997) i.e. International Conference of Building Officials and

Mander et al. (1998) Models. From Figure 13, it can be seen that the ICBO Model shows poor agreement with experimental results however the Mander Model predicted better results when compared with experimental results.

Key Observation:

Results show that the ICBO Model shows poor agreement with experimental results; however, the Mander Model predicted better results when compared with experimental results

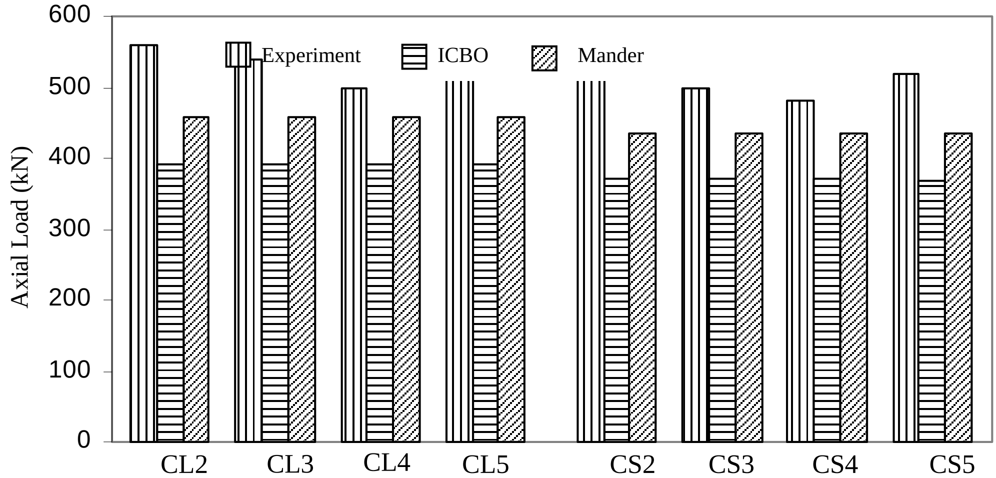

Figure 13: Comparison of experimental values with existing theoretical model

Table 4.3: Comparison experimental result with existing theoretical models

Specimen	Experimental Result (kN)	Theoretical Models			
		ICBO	% difference	Mander	% difference
CL1	380	---	---	---	---
CL2	560	391	43.22	459	22.00
CL3	540	391	38.11	459	17.65
CL4	500	391	27.88	459	8.93
CL5	560	391	43.22	459	22.00
CS1	360	---	---	---	---
CS2	540	370	45.95	435	24.14
CS3	500	370	35.14	435	14.94
CS4	480	370	29.73	435	10.34
CS5	520	367	41.69	435	19.54

4. CONCLUSIONS AND RECOMMENDATIONS

This paper was conducted to study the compressive strength of reinforced concrete rectangular columns confined with externally bonded GFRP fabrics. This study investigated three variables included slenderness ratio, spacing, amount and orientation, and number of plies of GFRP strips. From the experimental and theoretical investigations, following conclusions can be drawn:

- Experimental results show that the percentage gain in compressive load of the repaired specimens was ranging from 32% to 50% greater over the control specimens.
- It was found that increasing the spacing of strips decreases the ultimate compressive load of the repaired specimens.
- Results show that the ultimate compressive strength of the repaired specimens increased with increase in the numbers of GFRP strip layers.
- Result indicates that specimen specimens strengthened with orientation of ±45° attained a gain in compressive load of 8% greater than specimen with 0° orientation.
- Results confirm that the column with slenderness ratio of 3.33 contributed a maximum enhancement of 50% greater than column with slenderness ratio of 6.0.
- The theoretical investigation shows that the ICBO (1997) model predicted conservative results, whereas, the Mander *et al.,* (1988) model shows relatively better agreement with the experimental results.

Recommendations:

- Experimental study is required the behavior RC columns confined with different types of FRP.
- Investigation is need on in larger scale to simulate the actual repairing work for the structural member.

- Additional experimental work is essential with lower grade of concrete because most of older structures have been constructed with lower grade of concrete.

REFERENCES

[1.] *BRITISH STANDARDS INSTITUTION (BSI). "Structural use of concrete. Part 1: Code of practice for design and construction." BS8110, London, 1997.*

[2.] *KUMUTHA, R., VAIDYANATHAN, R., PALANICHAMY, M.S. "Behavior of reinforced rectangular columns strengthens using GFRP." Journal of, Cement and Concrete Composites 29, 609-615, 2005.*

[3.] *LI, G., KIDANE, S., PANG, S.S., HELMS, J.E, MICHAEL STUBBLEFIELD., A. 'Investigation into FRP repaired RC columns', (www.elsevier.com/locate/compstruct), 2003.*

[4.] *MANDER, J. B., PRIESTLEY, M. J. N., and PARK, R. "Theoretical stress-strain model for confined concrete." J. Struct. Eng., 114(8), 1804-1826, 1988.*

[5.] *RAGHU, H.A., MYERS, J .J. and NANNI, A. "Shear Performance of RC beams Strengthened in Situ with Composites." Report, University of Missouri, Rolla. Rectangular concrete columns', (www.elsevier.com/locate/cemconcomp), 2001.*

[6.] *YOUSEF, A. A. Durability of GFRP Rebars in Concrete Beams under sustained Loads at Severe Environments, Journal of Composite Materials, 40 (7), 623-637, 2006.*

ANNALS OF FACULTY ENGINEERING HUNEDOARA
– INTERNATIONAL JOURNAL OF ENGINEERING
copyright © University Politehnica Timisoara,
Faculty of Engineering Hunedoara,
5, Revolutiei, 331128, Hunedoara,
ROMANIA
http://annals.fih.upt.ro